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Deep-sea benthic foraminiferal turnovers in the early Eocene: The role of the PETM and ETM2

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Throughout the Cenozoic, deep-sea benthic foraminiferal communities have faced many periods of environmental turmoil. Three major, yet relatively gradual faunal turnovers occurred during the Eocene-Oligocene, middle Miocene and middle Pleistocene - all periods of pronounced cooling and increases in polar ice volume. In contrast, the Paleocene-Eocene Thermal Maximum (PETM; ~56 Ma) – a transient global warming event or hyperthermal - is characterized by a rapid extinction of 30-50% of all deep-sea benthic foraminiferal species (Thomas, 1998; 2007). So far, the exact cause(s) of this severe extinction event that devastated bathyal and abyssal faunas is not known. It is likely that a change in food-web structure, affected by high temperatures, a decrease in the oxygenation state of the oceans, calcite undersaturation, primary productivity or ocean current circulation changes played an important role in the benthic foraminiferal extinction (BFE) and in the establishment of the opportunistic fauna that characterizes the PETM itself (Thomas, 1998, 2007).

Historically, the earliest Eocene benthic foraminiferal associations were considered as a transitional fauna, recovering from the BFE and gradually recolonizing vacant niches and habitats. This transition from a Cretaceous-Paleocene *Velasco-type* fauna into a typical Eocene *Barbados-type* fauna appeared to be characterized by the gradual appearance of new taxa (Tjalsma & Lohmann, 1983; Berggren & Miller, 1989).

With the discovery of several Eocene hyperthermals similar to the PETM (e.g. Eocene Thermal Maximum 2; ETM2; ~53.7 Ma), the question arises of what role these events played in the development of early Eocene benthic communities. For instance, how did the impoverished benthic fauna cope with the environmental perturbations associated with these successive and smaller Eocene hyperthermals on short time scales? Did it become more or less sensitive to climatic and oceanographic changes? One can also wonder what the effects were on longer time scales. Did early Eocene hyperthermals hamper or stimulate recolonization of the benthic realm, and if so, in what way?

To answer these questions, we generated detailed quantitative benthic foraminiferal (>63 µm) data from two Deep Sea Drilling Project (DSDP) sites from the Bay of Biscay, NE Atlantic Ocean. The studied interval from bathyal DSDP Site 401 (~2 km paleodepth) ranges from NP9 to NP12 (~3 My) including the PETM and ETM2, while the studied material from abyssal DSDP Site 550 (~4 km paleodepth) encompasses a ~800 kyr interval including ETM2 and H2.

At DSDP Site 401, we observe the loss of typical Paleocene taxa (e.g. *Gavelinella beccariiformis*, *Eponides hillebrandti* and *Bolivinoides delicatulus*) at the onset of the well-expressed PETM (Bornemann *et al*., 2014), clearly demonstrating the abrupt nature of the BFE. However, the extinction rate is only about 20%, which is considerably lower than reported elsewhere (Thomas, 1998). Typical excursion taxa such as *Nuttallides umbonifera*, *Tappanina selmensis* and various abyssaminids dominate the core of the PETM, but are rapidly replaced by a relatively stable benthic association composed of *Epistominella minuta*, *Globocassidulina subglobosa* and various buliminids ranging up to ETM2 (D'haenens *et al*., 2012; *in prep*.). Following ETM2, the loss of buliminids and a minor but significant shift towards a *Cibicidoides*-dominated fauna illustrates the sudden transition towards a post-ETM2 benthic foraminiferal association (D'haenens *et al*., 2012). At the deeper DSDP Site 550, we also document a stable post-PETM benthic fauna dominated by abyssal taxa such as *Bolivinoides crenulata*, *Quadrimorphina profunda*, *N. truempyi*, *G. subglobosa and Gyroidinoides* spp. Similar to Site 401, a significant faunal transition occurs across ETM2, with the reduction of several taxa (*Q. profunda*, *Gyroidinoides* spp. and *G. subglobosa*) and the relative increase of others (*Anomalinoides* spp., *N. umbonifera* and *C. ungerianus*). The interval right after ETM2 is also characterized by the first occurrence of several taxa (e.g. *Pullenia quinqueloba*, *Buliminella grata*) that are known to persist throughout the Eocene (Fig. 1). Although of much lower resolution and using a different size fraction, data from nearby DSDP Site 549 corroborate these patterns (Reynolds, 1992).

Our results suggest that bathyal and abyssal NE Atlantic post-PETM benthic associations were all stable up to ETM2, despite their slightly different composition. Furthermore, we

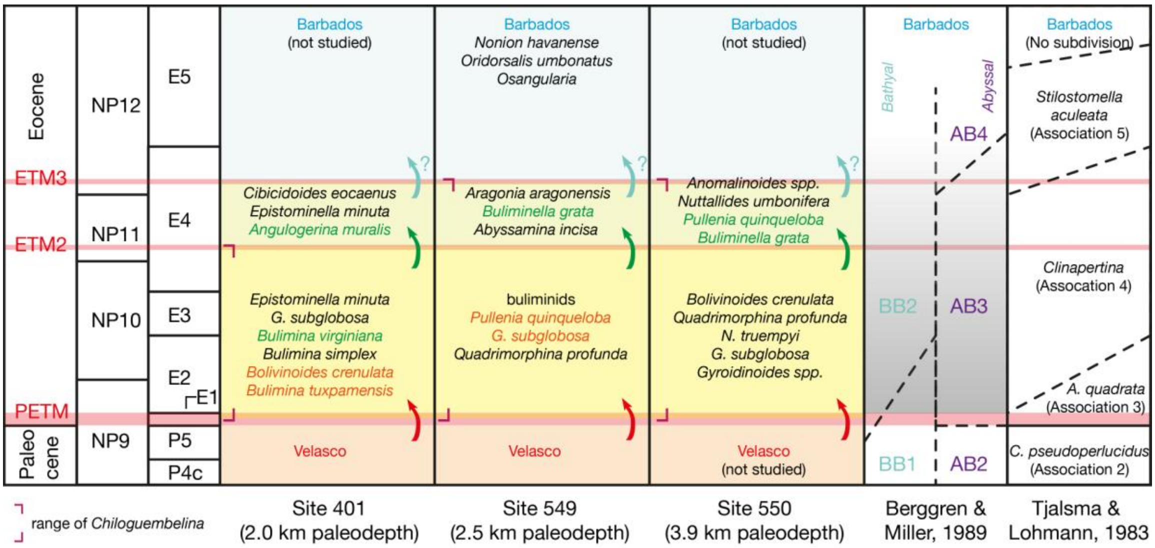

Fig.1 – Scheme of latest Paleocene to early Eocene benthic foraminiferal associations in the NE Atlantic (DSDP sites 401, 549 and 550). Across the PETM, site-specific (i.e. bathymetry-dependent) and stable early Eocene faunas replace the lost *Velasco-type* fauna. Another (minor) turnover, as indicated by the arrows, occurs across ETM2, resulting in new stable associations. Orange species names represent taxa that (virtually) disappear during the subsequent turnover, while green species names are taxa that have their lowest occurrence. Bathyal (BB)/abyssal (AB) zonations by Berggren & Miller (1989) and numbered benthic associations by Tjalsma & Lohmann (1983). The AB3/AB4 or *S. aculeata* association may correspond to an ETM3-related faunal turnover (teal arrows). Note that excursion assemblages (PETM, ETM2, ETM3) are not presented in this figure. Also note the lowest occurrence of the planktic foraminiferal genus *Chiloguembelina* at the onset of the PETM and its highest occurrence at ETM2 (401) or ETM3 (549 & 550).

show that a minor benthic turnover takes place contemporaneous with ETM2, independent of bathymetry. As such, this particular hyperthermal event appears to play a significant role in the development of Eocene benthic foraminiferal communities. One can argue that this particular transition is only limited to the NE Atlantic and has no significance on the global evolution of deep-sea faunas. Indeed, large and persistent environmental changes have been documented for the interval between the PETM, ETM2 and ETM3 in the Bay of Biscay (Bornemann *et al*., 2014; D'haenens *et al*., 2014) and there is no doubt that the benthic assemblages reflect them. Nevertheless, we note that global benthic foraminiferal data show similar patterns (e.g. Thomas, 1990; unpublished data; Stassen *et al*., 2012).

The historical view of a post-PETM transitional fauna that gradually recolonizes vacant niches and slowly evolves into a *Barbados-type* Eocene fauna may actually not be so accurate. Instead, based on our observations, we tentatively conclude that post-PETM faunas may have been in a relative state of stability ('stasis'), only to be kick-started into other stable states by subsequent early Eocene hyperthermals such as the ETM2 and ETM3 (Fig. 1). What impact other Eocene events (i.e. EECO-related hyperthermals, MECO, CAEs) had on long-term benthic ecosystem evolution, remains to be explored.

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